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Spatially Adaptive TV Broadcast System: Hardware in the Loop Operational Analysis

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***Abstract*—When a digital TV system is operating far in excess of the operational threshold, there is no discernible advantage to either the user or broadcaster due to the hard failure characteristics of digital TV. In a digital network, this threshold can vary due to changes in the propagation medium and user receiving equipment, necessitating a transmit power margin sufficient to cover all propagation and equipment variations. Hence if the system could be adaptively tuned to operate at just above the threshold, then significant energy savings could be made.**

A spatially adaptive system was evaluated through hardware-in-the-loop analysis; here a channel emulator was used to physically model array gain and fading conditions, and feedback nodes were constructed allowing broadcast powers to be manipulated based on evaluating user feedback. The effects of such a system on the UK Digital Terrestrial Television (DTT) network were evaluated and the advantages highlighted potential power savings of up to 2.1 dB being obtainable. This equates to an electricity reduction of between 33 million and 58 million kWh per year, saving between £3.5 million and £6.1 million ($4.4 million and $7.6 million) and reducing carbon emissions by between 13.7 million and 24 million CO_2e. This paper thus illustrates the potential energy savings for a DTT network, using the UK as a worked example.

***Index Terms*—Adaptive Broadcast Television, Hardware-in-the-loop, DVB-T, DTT, antennas, energy efficiency.**

I. Introduction

THE aim of the research presented in this paper was to examine the feasibility of a spatially adaptive broadcast system; a previous feasibility study in this area was covered in [1]. A spatially adaptive broadcast system is one where the broadcast powers and antenna patterns can be spatially manipulated via an adaptive algorithm, driven by user feedback supplied by a distributed monitoring network. The distributed monitoring network will consist of user receiving equipment with an internet link, such as Smart TVs, alongside professionally run calibration nodes. These calibration nodes will be used to add further accuracy to the feedback data supplied by users. In this way, the actual level of coverage in a broadcast area can be more accurately evaluated by a broadcaster. Fully optimising the broadcast powers of the network is something that cannot easily be addressed during network planning, as assumptions on the broadcast channel and receiving equipment installations can never fully reflect the actual broadcast conditions. Currently this problem is avoided by the use of excessive implementation margins which reduce the energy efficiency of the overall system. Thus further enhancements to the system can be made in order to overcome this problem as described and evaluated here.

Power control techniques and spatial filtering developed to improve mobile communications, such Channel State Information (CSI) and beamforming could be deployed in a broadcast network. If the broadcast towers had accurate CSI, then the entire broadcast system could be made more efficient as spatially adaptive beamforming techniques could be used to steer power to regions where coverage is needed. Broadcast power could be decreased further, or more users could be covered using the same broadcast power through better antenna pattern control, thus improving energy efficiency, reducing CO_2 emissions and lowering costs.

With a spatially adaptive broadcast system, the entire broadcast network can be made more energy efficient, as broadcast powers can be steered to areas where coverage is needed and/or reduced when propagation conditions allow. The important aspect of an adaptive TV broadcast system is that broadcast powers and beam patterns are only altered when the feedback conditions allow. In this way any potential loss of coverage is mitigated by not altering the broadcast conditions when there is insufficient feedback, leaving broadcast conditions as dictated by the network planning engineer.

A spatially adaptive broadcast system could also be linked with other forms of broadcast improvements, which are often brought under the umbrella of Future of Broadcast Television Initiative (FOBTV) [2]. Technologies include Hybrid broadcast broadband TV (HbbTV) [3], Redundancy on Demand (RoD) [4] and Dynamic Broadcast [5]. Recently there has been work into Bidirectional Broadcasting in Next Generation Broadcasting - Wireless (NGB-W) Networks [6]. These hybrid networks all use an internet link to improve the broadcast in various ways, not necessary the energy efficiency of the broadcast network. HbbTV merges Internet Protocol (IP) and traditional broadcast technologies to improve the viewing experience. Usually this takes the form of being able to launch an application that can provide further information and data about the show being watched. RoD uses an internet connection to request any missing packets from a weak or poor broadcast transmission, thus providing the viewer with an error free TV signal. This can be used to increase the effective broadcast range of network beyond the traditional coverage

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Figure 5 and related data has been reproduced from research previously presented in [1].

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area. Dynamic Broadcast optimises TV content distribution by making use of a secondary delivery system; in this way traditional broadcast techniques can be optimally used for large audience sizes and the second delivery system for smaller audience sizes. Dynamic Broadcast can also allow the traditional broadcast system to fall back to more robust modes, or even be switched off entirely to reduce the power consumptions of a transmitter. Bidirectional Broadcasting is a response to traditional broadcasting being increasingly unable to meet the demands of media services. The idea is to create a bidirectional network that integrates traditional live broadcast and Video on Demand (VoD) services. The return channel can be used for interactive TV services and can offer a more targeted user experience. Furthermore, the most recent Advanced Television Systems Committee (ATSC) 3.0 standard will include a return channel from users to service providers [7]. This return channel could be any existing technology and/or infrastructure such as wired and wireless internet or cellular networks. The rise in hybrid broadcast networks, internet on-demand services and return channels could provide information to the broadcaster to greatly improve the efficiency of broadcast networks through the use of the proposed spatially adaptive broadcast system.

Another area that could be improved with an adaptive broadcast system are White Space Devices (WSDs), many of which require either a sensing network or access to a database to ensure that there is no interference with incumbent users. The feedback from the distributed monitoring network could be used to improve the quality of WSD databases, and vice versa.

In this paper, the potential increase of energy efficiency of a broadcast network utilising a spatially adaptive broadcast system is realised in laboratory conditions through the use of hardware in the loop analysis. A TV signal was constructed and the broadcast propagation channel was emulated using a channel emulator. Receiving nodes were constructed to act as viewers and professionally calibrated nodes within the entire spatially adaptive broadcast system. Feedback from these nodes was used to adapt and control the broadcast signal and channel emulation to simulate a spatially adaptive broadcast system. The possible reduction of energy and electricity usage was calculated and applied to the UK DTT network to evaluate the potential monetary improvements of a spatially adaptive broadcast system.

Section II will outline the hardware-in-the-loop experimental set up for testing the adaptive broadcast system. Section III explores the use case scenarios and parameters, with section IV adding further analysis and parameter optimization by including adaptive constraints. Section V provides a costing analysis of the savings a spatially adaptive system could bring, both in terms of electricity saved and the environmental impacts. Section VI summarises and concludes the paper and presents the final recommendations for a spatially adaptive broadcast system.

II. Hardware Set-up

A. Introduction

In order to construct the hardware model of the adaptive system, a broadcast tower, propagation channel and user feedback/calibrated nodes had to be constructed in our laboratory. The broadcast signal came from an Edision High-Definition Multimedia Interface (HDMI) to Digital Video Broadcasting - Terrestrial (DVB-T) modulator, which was set to create a UK compliant DVB-T signal used for the Public Service Broadcaster (PSB) Multiplexes (MUXs). The HDMI feed was taken from the British Broadcasting Corporation (BBC) news channel being delivered by the BBC iPlayer service. This ensured that a stable DVB-T signal could be maintained for testing purposes. The HDMI to DVB-T modulator had a quoted Modulation Error Rate (MER) of 35 dB [8], which was deemed sufficient for the purposes of this test. DVB-T accounts for five of the main seven MUXs in the UK, but it is believed that a complete switch to Second Generation Digital Video Broadcasting - Terrestrial (DVB-T2) will occur in the future. DVB-T is used throughout this experiment due to the modulator hardware available at the time, but an adaptive system would also work with DVB-T2.

The DVB-T signal was then fed into an Anite[1] [10] F8 channel emulator [11]. The F8 consists of 8 external Radio Frequency (RF) inputs and outputs, and can create up to 64 internally emulated wireless channels. One RF input was used for the DVB-T modulator that was connected to up to 8 internal channels and then to the corresponding RF output connection. In this way, the input signal to all channels was identical and the number of internal F8 channel responses was limited to the number of RF outputs. This allowed up to 8 separate receiving nodes.

Each channel in the emulator was loaded with the European Telecommunications Standard Institute (ETSI) channel model for DVB-T as seen in table I; this is a 6 tap Rayleigh fading model, with static receivers. Shadowing variations could then be applied to each channel to simulate the changing propagation of a TV signal; this allowed up to 8 individual outputs with different shadowing profiles. Each RF output on the F8 could be assumed to be an individual antenna or part of an antenna array at the broadcast tower capable of providing coverage to a specific area within the larger broadcast area. This assumption had to be made to allow the beamforming to take place. Figure 1 shows the channel model with sinusoidal shadowing; sinusoidal shadowing was applied for calibration purposes.

Each F8 output could then be fed into individual National Instruments [12] Universal Software Radio Peripherals (USRPs) [13] operating as receiver hardware or professionally calibrated feedback nodes. These devices would provide feedback on the Quality of Service (QoS) of the individual channels. The USRPs were assumed to be placed in optimal locations within the assumed broadcast area of each channel, for example at the fringe areas of the network. It can be assumed that regular users who are closer to the broadcast tower than the feedback node(s) would receive a higher signal power from the broadcast tower as they would be less affected by propagation effects. This allowed the assumption that the feedback would provide the best available coverage estimation for each channel/antenna element. The power of the RF

[1] Anite is now part of Keysight Technologies [9]

TABLE I
THE ETSI 6 TAP CHANNEL MODEL FOR DVB-T

Path Number	Relative Path Delay (ns)	Relative Path Amplitude (dB)	Phase Shift (deg)	Doppler Spectrum
1	0	-8.9	-165	NONE
2	450	0	0	NONE
3	550	-2.1	125	NONE
4	1850	-4.6	-26	NONE
5	2700	-6.3	-150	NONE
6	3150	-6.9	164	NONE

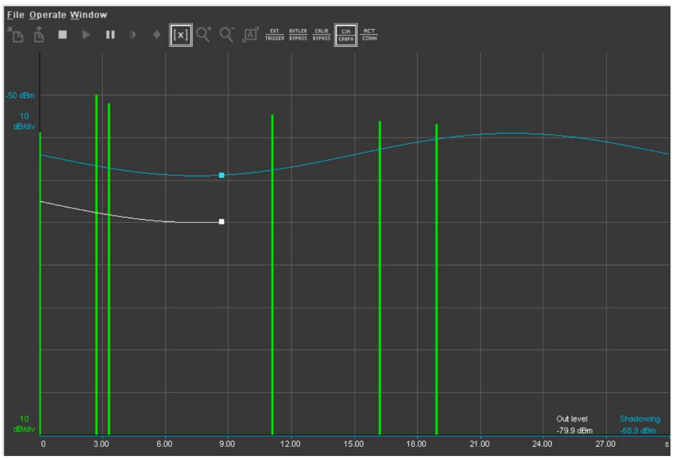

Fig. 1. Channel Model in the F8, with added sinusoidal shadowing for testing purposes.

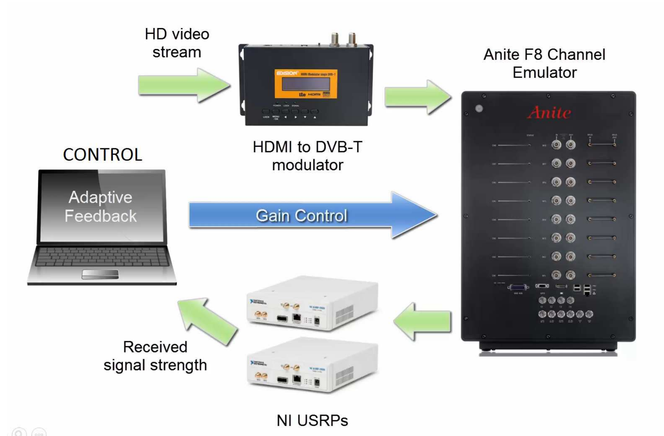

Fig. 2. Diagram of the hardware set up for lab based simulation.

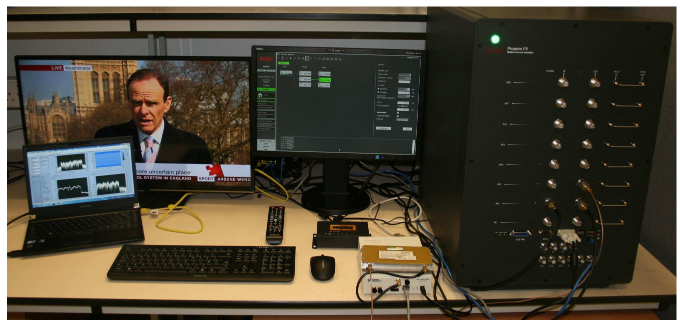

Fig. 3. Lab set up used for testing. Only one USRP is shown.

outputs and gain of an internal channel could be measured by the F8 and could also be used as feedback. This feedback would be collected in a central computer, which would issue commands to the F8 to adapt the individual channel gains to overcome the effects of the shadowing model on that particular channel.

Figure 2 illustrates the physical system architecture of the experimental set up. Figure 3 shows the set up in the lab. The planned operation was as follows:

1) Generate DVB-T signal
2) Feed signal into the F8 at a fixed output power to simulate broadcast
3) Apply pattern simulations/shadowing to channels within the F8 to emulate field response of adaptive broadcast tower at specific look and range directions
4) Receiver (Rx) measures the QoS of each individual emulated channel
5) Feedback QoS information to CONTROL
6) CONTROL then compares the QoS metric with the ideal receive power and alters the pattern simulations and/or broadcast power based on the feedback and the candidate control algorithm
7) Repeat steps 3–6

B. Defining the Signal Quality Metric

Prior to running the full model, a single receiver set up was used in order to check the validity of the hardware model and to provide benchmark testing to determine the value of the QoS metric to be used. Without fully decoding the DVB-T signal, the power-in-band and an approximation of Carrier to Noise Ratio (C/N) of the channel was used.

DVB-T network planning guides [14] have minimum receive powers for complete decoding in Rician and Rayleigh channels for the different data rates available within DVB-T; it is possible to adapt these receive powers for the correct channel frequency and bit rates being used, in this case 698 MHz and 24 MBits/s. The minimum receive powers can be converted into minimum field strength in dBμV/m to provide a coverage location probability of 70% or 95%. These coverage values were chosen as they are same as the current UK network [15], [16]. Alternative coverage probabilities could be used for planning parameters in different countries.

The F8 was loaded with the ETSI model for a DVB-T channel. To find the failure rates of this channel, the output

TABLE II
F8 TARGET METRICS FOR VARIOUS CHANNEL TYPES.

	Min		70% Probability		95% Probability	
	dBm	C/N (dB)	dBm	C/N (dB)	dBm	C/N (dB)
Rician	-80.9	17.3	-78.0	20.2	-71.9	26.3
Rayleigh	-77.9	20.3	-75.0	23.2	-68.9	29.3
DVB-T Lower	-80.6	17.6	-77.7	20.5	-71.6	26.6
DVB-T Upper	-79.6	18.6	-76.6	21.5	-70.6	27.6

power of the F8 was lowered gradually until a connected Samsung UE32H5500 TV failed, with the output power being noted just before failure occurred. This gave a failure power for the ETSI channel model between -79.6 dBm and -80.6 dBm. The failure value changed based on the actual data rate of the MUX, which varied based on the content being modulated. This is because an increase in null packets for when the data rate drops masks lower error rates.

Required signal levels in dBm for all possible channels and coverage probabilities were calculated using the field strength required for 70% and 95% coverage probability. This can be seen in table II.

C. Set-up and Preliminary Testing - Defining Log-normal Shadowing

Shadowing profiles were added to individual DVB-T channels to simulate a fluctuating channel for the adaptive process. The F8 has the capability of simulating a time varying shadow profile, which was used to simulate channel impairments. Figure 5 shows an example of real world channel fluctuations observed over 72 hours. The data in Figure 5 was taken using a National Instruments USRP running LabView and connected to a correctly aligned rooftop aerial. It was tuned to channel 49, 698 MHz, which is the the PSB1 MUX from the Mendip Broadcast tower in the South West of England. A channel filter was used to compensate for the wideband nature of the USRP receiver; data was sampled every second and the power across the frequency band was taken. The weather at the receiver was also recorded using the BBC weather service. The received power fluctuates 6.6 dB over the 72 hour period. Taking the mean power over 5 minutes, the range drops to 2.2 dB. The gradual variations do not appear to be obviously tied to the weather conditions at the receiver. The reasons for the rapid fluctuations in mean received power are unclear (possibly local interference), but the gradual variations that are obviously due to propagation conditions enforces the notion that an adaptive system based on user feedback is preferred over a one-time tune-up to the network.

The log-normal shadowing profiles were defined based on the data shown in figure 5. They are defined internally within the F8 as followed:

- Profile type: Log-normal standard deviation
- Resolution: 0.001 s
- Correlation Time: 15 s
- Repetition Time: 90 s

A log-normal shadowing profile was chosen to enable emulation of 90 seconds of channel variation. Thus allowing enough time for 72 seconds of data logging, which could be scaled up to 72 hours. The deviation was changed to create three channel models with varying fluctuations, small, medium and large, with values of 0.75 dB, 1.5 dB and 2.5 dB respectively. These values were chosen based on the 72 hour data logging seen in figure 5.

These channel models were logged over the full 90 second duration, with readings taken from within the F8. Each channel was run with a fixed channel gain of -30 dB, with the average of three separate runs being taken; the results are shown in figure 4. The full Rate of Change (RoC) between values was calculated and the summary of these results is shown in table III.

TABLE III
SUMMARY OF THE THREE LOG-NORMAL SHADOWING PROFILES

	Small 0.75 dB deviation		Medium 1.5 dB deviation		Large 2.5 dB deviation	
Channel Gain	-30 dB	-35 dB	-30 dB	-35 dB	-30 dB	-35 dB
Range	2.87	2.87	3.47	3.47	11.00	11.00
Mean	-57.87	-62.87	-61.02	-66.03	-64.51	-69.52
Standard Deviation	0.654	0.654	0.772	0.776	2.724	2.717
Max Positive RoC	0.50	0.54	0.87	0.87	1.70	1.70
Max Negative RoC	-0.50	-0.40	-0.96	-1.07	-2.00	-1.81
1st Percentile	-0.38	-0.37	-0.88	-0.92	-1.42	-1.61
5th Percentile	-0.30	-0.28	-0.57	-0.54	-0.90	-0.94
95th Percentile	0.33	0.30	0.60	0.60	0.83	0.90
99th Percentile	0.44	0.42	0.77	0.79	1.42	1.43

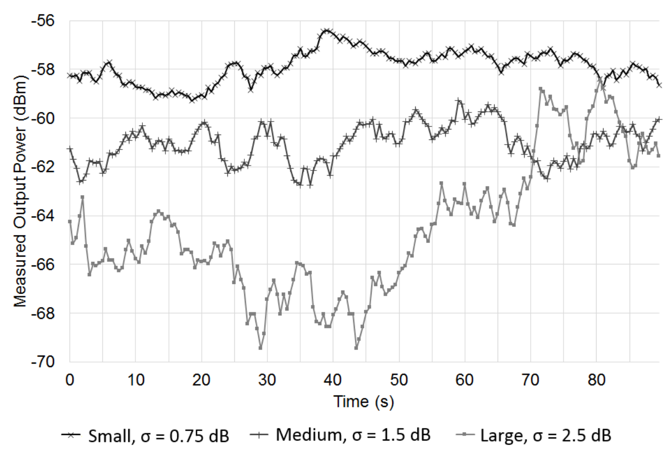

Fig. 4. The effects of the three types of log-normal shadowing on a DVB-T channel. The three types of log-normal shadowing correlates to the different standard deviations used; small, 0.75 dB; medium 1.5 dB and large, 2.5 dB

D. Feedback Data Operation

The control for the adaptive system operated in the following way. National Instruments LabVIEW [17] was used to get power in band values from USRPs attached to the F8 outputs. MATLAB [18] was used to query the F8 about current channel gain and output post shadowing, and set new gain values. LabVIEW communicated with MATLAB using an internal Universal Datagram Packet (UDP) socket; all control was carried out within the MATLAB environment. This allowed an adaptive system that could operate either with feedback from USRPs or from the reported output values of the F8.

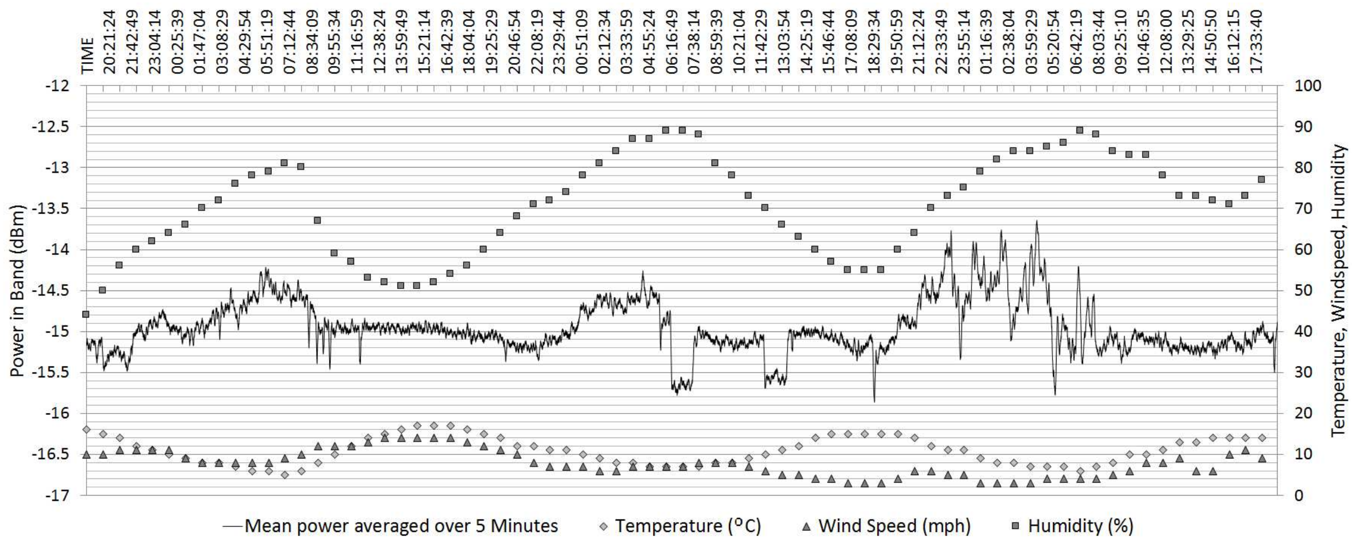

Fig. 5. 72 Hour Test of the received power in band of the PSB1 MUX from the Mendip Broadcast Tower. The PSB1 MUX is broadcast on channel 49 (698 MHz) using DVB-T. Data was taken using a roof top aerial and a National Instruments USRP operated through LabView. This figure has been reproduced from [1].

TABLE IV
THE FIXED GAINS FOR ALL CHANNELS AND SHADOWING PROFILES. THE TARGET VALUES ARE THE 95% COVERAGE PROBABILITY FROM TABLE II FOR THE INDICATED CHANNEL.

	Target Value	Small	Medium	Large
Rician	-71.9 dBm	-43.1 dB	-38.3 dB	-32.5 dB
Rayleigh	-68.9 dBm	-40.1 dB	-36.3 dB	-29.5 dB
DVB-T Lower	-71.6 dBm	-42.8 dB	-38.0 dB	-32.2 dB
DVB-T Upper	-70.6 dBm	-41.8 dB	-37.0 dB	-31.2 dB

TABLE V
CHANNEL STATISTICS FOR NON-ADAPTIVE, AND F8 AND USRP CONTROLLED ADAPTIVE CHANNELS WITH LARGE LOG-NORMAL SHADOWING. THE TARGET VALUE USED WAS UPPER DVB-T, OF -70.6 DBM.

	Adaptive (dBm)	Non-adaptive (dBm)	USRP Measured (dBm)	Adaptive Gain (dB)	USRP Gain (dB)
Mean	-70.6	-66.0	-70.6	-35.8	-34.7
Median	-70.7	-66.5	-70.6	-35.3	-34.0
Min	-72.4	-70.3	-72.0	-42.1	-41.2
Max	-66.8	-59.6	-68.3	-31.0	-30.1
Range	5.6	10.7	3.7	11.1	11.1
Standard Deviation	0.69	2.68	0.61	2.68	2.70

III. EXPERIMENT OPERATION

A. Applying Adaptive Feedback

With the complete set up, it was then possible to apply adaptive feedback to alter the gain to overcome the effects of the log-normal shadowing on that particular channel and look direction. The F8 received a fixed input power in dBm from the DVB-T modulator. For each log-normal shadowing profile, the appropriate channel gain was calculated to ensure that the output signal never dropped below the required power for 95% coverage probability from table II.

Table IV shows the fixed gains for all combinations of channel and shadowing profiles used. This is the minimum gain of the channel required to overcome the worst observed shadowing. This is why the gain for the large shadowing profile is higher than the small profile, as there is a greater variation of the fluctuation seen on this channel.

Each channel and shadowing profile was run with feedback from a single USRP and the reported output from the F8. Two USRPs were used for these tests and were connected to two separate F8 outputs. Each USRP recorded the mean power in band and the F8 recorded the current output of a different RF output connected to a Samsung UE32H5500 TV; the respective data was taken every 500 ms. This feedback data was then compared to the failure point of DVB-T and a new channel gain was then calculated and allocated to set the output of the signal to the target value for that specific channel to ensure that the failure point was only just met. This meant that gain per each individual channel was altered over time depending on what was being observed. This was done for both the F8 channel and the USRP controlled channels. A non-adaptive channel was also recorded for comparison, as well as the output of the F8 channels that was connected to the USRPs.

Figure 6 shows the power change over 75 seconds from log-normal fading, with the Upper DVB-T target value of -70.6 dBm. Figure 7 shows how the gain is altered over time to compensate for the fluctuations seen on the channel from the log-normal shadowing. The summary of the channel statistics can be seen in table V. Here it can be seen that adapting the channel lowers the observed mean value.

B. Analysis of Feedback Data

Without the ability to adapt the broadcast power and maintaining a received power that never drops below the 95%

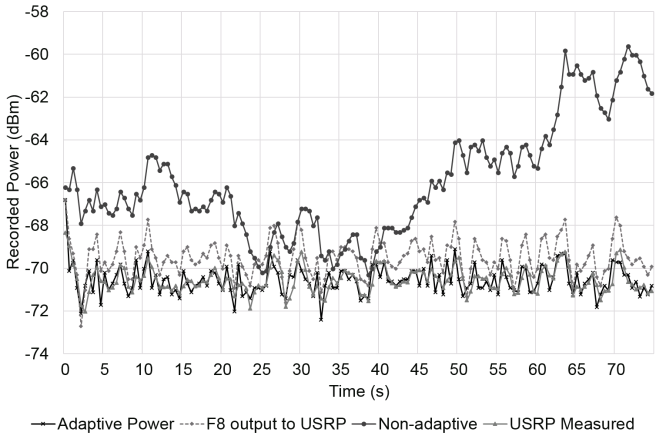

Fig. 6. Upper DVB-T target value with the large log-normal shadowing.

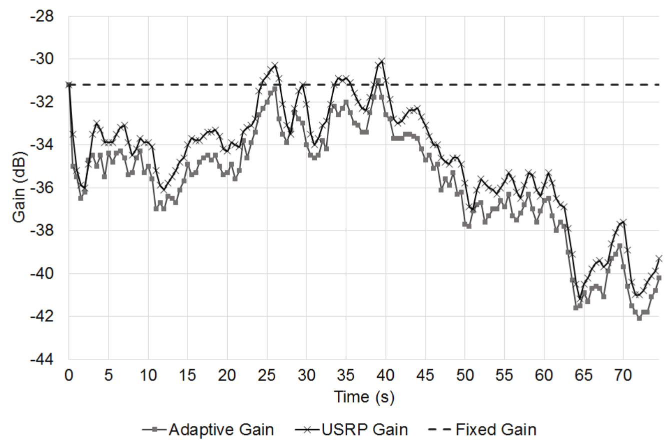

Fig. 7. Adaptive Gains for the Upper DVB-T target value, operating in an adaptive channel. The standard deviation used was for the large log-normal value of 2 dB.

coverage probability value, means that for 71% of the time the power is at least 3 dB in excess of the desired value. Table V illustrates this fact; for the non-adaptive channel, the minimum recorded value is -70.3 dBm, but the mean value is -64.0 dBm, and the maximum value is -59.6 dBm. Operating far in excess of the target value can also be seen in figure 6, especially after 42 seconds, where the received broadcast power continues to rise significantly more than the target value of -70.6 dBm.

Comparing the non-adaptive with the adaptive channels, the mean value drops to -70.6 dBm. However, the minimum value has also dropped to -72.4 dBm, which is below the desired value of -70.6 dBm. This means that the signal can no longer be considered above the 95% coverage probability; in this instance the signal is only above this value and therefore operating at the desired level of coverage, 45.3% of the time.

Table V also shows how adapting the broadcast gain greatly reduces the fluctuations of the received signal. Without any adaptation the signal range is 10.7 dB, with adaptation this falls to 5.6 dB or 3.7 dB for the USRP measurement. This adaptation comes via changing the broadcast gain by a range of 11.1 dB. This can be seen clearly in figure 7; this figure also shows that for the majority of the time the gain is less

TABLE VI
OFFSET VALUES FOR THE THREE SHADOWING TYPES, CALCULATED FROM THE WORST POSSIBLE RoC SEEN IN TABLE III

	Min Value	1st Percentile	5th Percentile
Small	0.54	0.44	0.33
Medium	1.07	0.92	0.60
Large	2.00	1.61	0.94

than that of the non-adaptive channel gain.

The biggest reduction in gain in figure 7 can be seen after 42 seconds; this is to offset the rising power after 42 seconds of the non-adaptive channel as seen in figure 6. The mean adaptive gain falls from -31.2 dB to -35.8 dB for the adaptive gain, and -34.7 dB for the USRP measurements. This difference is because of the added cable loss between the F8 and the USRP. This equates to between 4.6 dB and 3.5 dB saving on the mean gain through using adaptive broadcast on this particular shadowing profile.

C. *Finding an Operational Offset*

With the analysis seen in the previous section, the signal was only above the required value for 95% coverage probability 45.3% of the time. An operational offset to the target threshold would therefore be required to counteract this problem; an adaptive system should ideally operate at the same level of coverage as a non-adaptive system.

Studying the data on the shadowing profiles in table III, it was possible to calculate an offset to the target threshold. The offsets were based on the worst RoC observed between values. The 1st and 99th percentile, 5th and 95th percentile, and max positive and negative RoC were compared. The offset had to take into account both positive and negative change, which is why these values were grouped together. The offset values can be seen in table VI.

The values in table VI can be used to give flexibility to the network planning engineer, based on how robust they want an adaptive system to be under normal channel fluctuations seen in the log-normal shadowing profiles. To ensure that the adaptive channel will never fall below the desired coverage probability, then the minimum value offset would be used. If some drop in coverage was deemed acceptable, then the 1st percentile or 5th percentile offset could be used. If 70% coverage probability value was to be used, then the minimum offset must be used, as any drop below the 70% coverage probability is considered not serviced.

Applying the offset values to the data for DVB-T upper and large log-normal fading as shown in figures 6 and 7 can be seen in table VII.

In the case of DVB-T upper with large log normal shadowing, using the minimum offset value of 2 means that 100% of the time the signal is above the threshold for 95% coverage probability. Using the 1st percentile offset, results in a slight fall to 99.3% of the time; for the 5th percentile offset, the coverage drops to 96.7% of the time. It is up to the network planning engineer whether this loss in coverage probability is acceptable for the extra power savings; using the 5th percentile offset means a further 1.1 dB of power can be saved. In all

TABLE VII
TIME SPENT ABOVE COVERAGE RATES FOR DVB-T UPPER VALUE WITH LARGE LOG-NORMAL SHADOWING, WITH OFFSET VALUES FROM TABLE VI

	Minimum Value Observed	Time spent above 95% coverage probability	At least 70% coverage probability
No Offset	-72.42 dBm	45.33%	TRUE
Include min offset	-70.42 dBm	100.00%	TRUE
Include 1st percentile	-70.81 dBm	99.33%	TRUE
Include 5th percentile	-71.48 dBm	96.67%	TRUE

TABLE VIII
SUMMARY OF MEAN GAIN SAVINGS IN DB FOR ALL CHANNELS AND SHADOWING PROFILES

	No Offset	Min Offset	1st Percentile	5th Percentile
Small Log Shadowing				
Rician	0.81	0.27	0.37	0.48
Rayleigh	0.82	0.28	0.38	0.49
DVB-T Lower	0.81	0.27	0.37	0.48
DVB-T Upper	0.79	0.25	0.35	0.46
Medium Log Shadowing				
Rician	2.38	1.31	1.46	1.78
Rayleigh	1.38	0.31	0.46	0.78
DVB-T Lower	2.37	1.30	1.45	1.77
DVB-T Upper	2.38	1.31	1.46	1.78
Large Log Shadowing				
Rician	4.39	2.39	2.78	3.45
Rayleigh	4.43	2.43	2.82	3.49
DVB-T Lower	4.54	2.54	2.93	3.60
DVB-T Upper	4.58	2.58	2.97	3.64

situations, using any of the offsets provides a greater level of coverage probability than without any offset. The signal strength never drops below the 70% coverage probability value, so the signal can always be considered adequate.

The test was repeated with all combinations of channel variables as seen in table IV. It is worth noting that 3 out of a possible 12 combinations failed to have above the relevant 95% coverage probability 100% of the time when the minimum offset was applied. This will be the result of the log-normal channel experiencing a slightly higher than expected RoC for that particular data run.

Table VIII shows the summary of the mean gain savings that are achievable with all combinations of shadowing profiles and channel models. Without any offset, the maximum observed gain reduction ranged between 0.8 dB and 4.6 dB, however this did lead to a severe drop in coverage. Using the various offsets reduced the possible mean gain reductions, but maintained better coverage. The minimum offset always maintained the same level of coverage as the non-adaptive case.

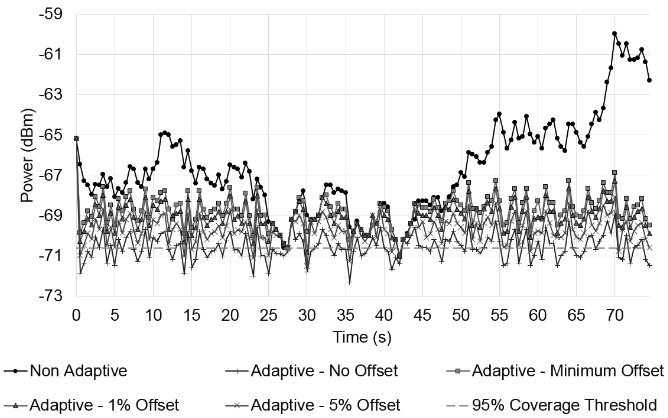

Fig. 8. Adaptive output with gain limit and various offsets.

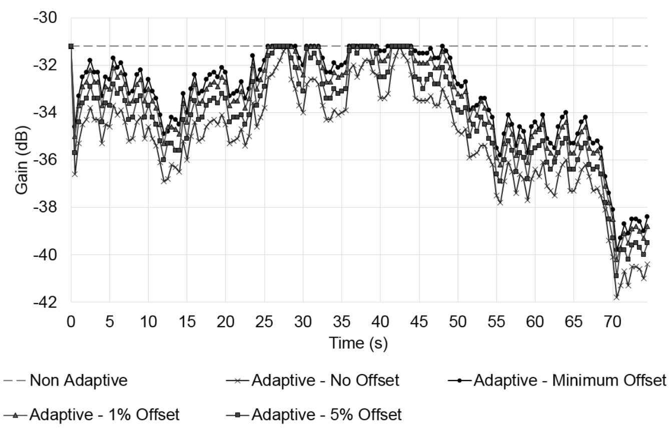

Fig. 9. Adaptive gains with max gain limit and various offsets.

The adaptive gains in figure 7 occasionally go above the fixed gain for the non-adaptive system. This will be exacerbated by applying the offset, as the entire gain will be increased accordingly. To prevent this, the range of values the gain of the channel can have, will be bounded by a maximum and minimum gain. This will now be explored in section IV.

IV. ADAPTIVE GAIN CONSTRAINTS

A. Fixing an Upper Gain Limit

To be able to compare the gains and powers data, the same large log-normal shadowing profile and DVB-T upper target value was used. The adaptive system was run again using the same allocation method, but limiting the maximum gain to -31.2 dB. The results of the broadcast power can be seen in figure 8 and the gains can be seen in figure 9.

Figure 8 further illustrates the necessity of some form of offset, as without the offset the adaptive coverage frequently drops below the 95% coverage threshold. The effect of the upper gain limit is obvious from where the adaptive gains level off in figure 9; this can be seen at 26 and 42 seconds where the adaptive gains are being clipped by the non-adaptive gain.

Table IX shows a summary of the effects of applying offsets to the adaptive channel. The non-adaptive channel drops below

TABLE IX
SUMMARY OF THE EFFECTS OF APPLYING VARIOUS OFFSETS TO AN ADAPTIVE SYSTEM.

	Non Adaptive	No Offset	Minimum Offset	1st Percentile	5th Percentile
Time Above Threshold	99.33%	52.67%	99.33%	98.67%	92.67%
Seconds below Threshold	0.5	35.5	0.5	1	5.5
Mean Gain	-31.20 dB	-35.07 dB	-33.27 dB	-33.59 dB	-34.20 dB
Mean Power Reduction	0.00 dB	3.87 dB	2.07 dB	2.39 dB	3.00 dB

the required threshold for 0.5 seconds; this will be down to either slight discrepancies of the input power into the F8 or a slightly faster RoC than expected. What is important are the comparisons between the non adaptive coverage and the coverage expected with the various offsets. Using the minimum offset creates a signal that has identical coverage characteristics of the non-adaptive case, but operates with a mean gain of -33.3 dB, 2.1 dB lower than the non-adaptive case. If coverage for the given system was allowed to be reduced by a small amount, this mean gain could be reduced further; mean gain reductions of 2.4 or 3 dB could be achieved. Whether the coverage can be lowered further is dependent on the allowed system losses as dictated by a network planning engineer.

B. Fixing an Upper and a Lower Gain Limit

The same large log-normal shadowing profile and DVB-T upper target value was used. The adaptive system was run again, but this time including an upper gain limit of -31.2 dB and a lower gain limit 3 dB lower than this of -34.2 dB. Through simulation it was found that reducing broadcast gain by extensive amounts could result in severe coverage loss when there is low levels of user feedback. This was due to a false positive, where a few feedback nodes skewed the data making the broadcaster assume that there was a greater level of coverage then there was observed by non-feedback nodes. A maximum gain reduction of 3 dB was used within this analysis.

The results for broadcast power can be seen in figure 10 and the gains can be seen in figure 11.

Figure 10, like figure 8, illustrates the need for some form of offset as the adaptive coverage frequently drops below the 95% coverage threshold. Limiting the amount the gain can be reduced, improves the time the coverage is above the requisite threshold. This can be seen by the time spent above the threshold increasing from 52.7% to 78.7%. This drop in coverage will still be too high, so some form of offset will be needed.

The impact of limiting the amount the gain can be reduced can be seen very clearly in figure 11. Above 52 seconds the

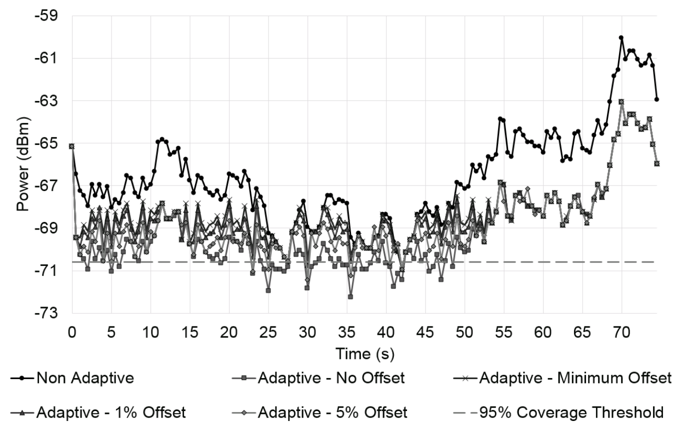

Fig. 10. Adaptive output with an Upper and Lower Gain limit and Various offsets.

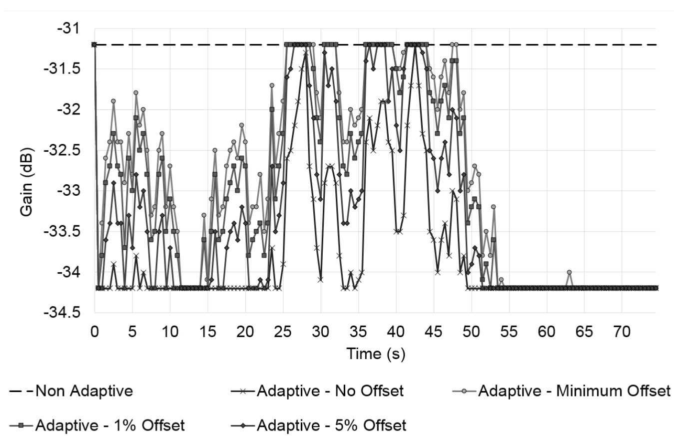

Fig. 11. Adaptive Gains with an Upper and Lower gain limit and various offsets.

gain is being limited by the lower gain limit; this is also reflected in figure 10 above 52 seconds.

Table X shows a summary of the effects of limiting the upper and lower gains of an adaptive channel. Again like the data in table IX, the same level of coverage for the non-

TABLE X
SUMMARY OF THE THE EFFECTS OF APPLYING VARIOUS OFFSETS TO AN ADAPTIVE SYSTEM, AND USING AN UPPER AND LOWER GAIN LIMIT.

	Non Adaptive	No Offset	Minimum Offset	1 Percentile	5 Percentile
Time Above Threshold	99.33%	78.67%	99.33%	98.67%	96.00%
Seconds below threshold	0.5	16	0.5	1	3
Mean Gain	-31.20 dB	-33.76 dB	-32.83 dB	-33.00 dB	-33.32 dB
Mean Power Reduction	0.00 dB	2.56 dB	1.63 dB	1.80 dB	2.12 dB

adaptive channel and adaptive channel are observed but with a mean gain reduction of 1.6 dB. If some coverage losses were acceptable, then the gain could be reduced by 1.8 dB or 2.1 dB; this will be dependent on the level of losses acceptable to the network planning engineer.

C. Observations

Limiting the amount the gain can be altered can further enhance an adaptive system by adding safeguards to the adaptive process. In this case, it ensured that the gain could never be increased further than that allocated during network planning, or reduced to a level that would be deemed too low. This does assume that the original gain as calculated during network planning is accurate; in the case of table IX and table X the non-adaptive gain does create a signal that drops for 0.5 seconds below the required threshold. Even though this gain wasn't the correct gain to ensure a signal that was always above the threshold for a non-adaptive system, an adaptive system can maintain the same level of coverage while reducing the mean gain of the system.

Coverage offsets are required to ensure that coverage can be maintained for a lower average broadcast power. If further losses are deemed acceptable in a system, then the offset value can be slackened; this will be dependent on the strict system losses that are acceptable to the network planning engineer.

V. Cost Analysis of a Spatially Adaptive Broadcast System for the UK DTT Network

A. Introduction

Before any implementation of a spatially adaptive broadcast system could be installed and operated, a full cost analysis would have to be undertaken. Broadcast savings need to be set against the cost of implementation and yearly running costs to find the true benefits of an adaptive system. A cost analysis was undertaken as part of this research, and a summary is presented here.

B. Estimated Costs of the Current Broadcast System

Crystal Palace, London, UK operates with 6 MUXs at 200 kW Effective Radiated Power (ERP) and one at 42 kW ERP. Antenna gain is approximately 10 dB. Each MUX is individually amplified. This means the total output of the Power Amplifiers (PAs) can be estimated as 125 kW. The actual efficiencies of the PAs present are unknown. However, the latest Rohde and Schwarz amplifiers operate at 28% efficiency under normal operating conditions [19]. The older PAs at the broadcast sites can be estimated to be less than this, so an assumption of 20% can be made. To incorporate any further losses in the transmission, the complete efficiency of a broadcast tower can be estimated to be between 10–20%; an estimated total of 625–1250 kW of electricity is needed for Crystal Palace.

There are 49 transmitter sites in the UK that operate at or above 10 kW ERP [20]; assuming 6 multiplexes and an average antenna gain of 10 dB yields an average total PA output of 39 kW per tower and total of about 1900 kW for all 49 sites. Assuming a total efficiency between 10–20%, the estimated running costs can be seen in table XI.

TABLE XI
The total estimated carbon emissions and running costs for different energy efficiencies at transmit sites above 10 kW ERP.

Efficiency	**10%**	**20%**
Electricity per year	166,440,000 kWh	83,220,000 kWh
Emissions	68,581,602 kg CO_2e	34,290,801 kg CO_2e
Carbon	18,722,777.3 kg	9,361,388.7 kg
Monetary Cost	£17,476,200	£8,738,100

C. Summary of the Installation and Running Costs of a Spatially Adaptive System

Reusing as much of the current broadcast hardware as possible is important to keep implementation costs to an absolute minimum. The broadcast towers cannot be moved, and their current locations will need to be incorporated into a spatially adaptive system. The antenna arrays/elements and amplifiers at the broadcast towers will also have to be reused. During Digital Switch Over (DSO), all broadcast towers were updated to accommodate digital transmission, this included new multi panel array systems. It has been assumed throughout this research that such multi panel array systems with further engineering work could be used for the necessary beamforming. Such an assumption had to be made for research to continue. Further hardware to run the adaptive algorithms and further wiring to allow beamforming to take place will be the main cost to the broadcasters. DSO cost a total of £157.3 million ($195.1 million), but only £30.8 million ($38.2 million) was for the operational costs of the switch over [21]. A full analysis of the costs of implementing the necessary hardware alterations required for a spatially adaptive system are not explored here. However, it can be assumed that the cost of altering the current DTT network will be less than £30.8 million (not adjusted for inflation), as the key hardware components already in place will remain.

The monetary and environmental costs of running an adaptive network can be split between user costs and broadcaster costs. The user costs are those of TV viewing equipment and electricity used when relaying the data back to the broadcaster. The broadcaster costs are those for running the servers and computing costs to store the user feedback data, and then run the allocation algorithm. The monetary costs to the user is considered to be non-existent, as all hardware is assumed to be in place; feedback will come from already owned user equipment such as Smart TVs.

To operate the servers and processors assuming total feedback from the 26.5 million UK homes with a digital TV [22], at the rate of one UDP packet per user per second to a central location would require no more than 5 kW of power, which would require 43,800 kWh for an entire year, creating 18,048 kg CO_2e[2], or 4927 kg of carbon, at a cost of £4599 at January 2017 prices. These costs were based on the running costs of servers [23] and current Intel [24] processors [25]. The emissions were calculated with the National Energy

[2]Equivalent carbon dioxide, CO_2e, is the UK measure for the equivalent greenhouse gasses released into the atmosphere; it includes gases other than CO_2, such as methane and nitrous oxide.

TABLE XII
MAXIMUM PREDICTED YEARLY REDUCTIONS AN ADAPTIVE BROADCAST SYSTEM CAN PROVIDE AT THE LARGEST 49 BROADCAST SITES IN THE UK, ASSUMING A BROADCAST TOWER EFFICIENCY OF 10%.

Predicted ERP Reductions	20%	35%
Electricity Reduction per Year	33,288,000 kWh	58,254,000 kWh
Emission Reductions	13,716,320 kg CO_2e	24,003,561 kg CO_2e
Carbon Reductions	3,744,555.4 kg	6,552,972.2 kg
Money Saved	£3,495,240	£6,116,670

Foundation (NEF) carbon calculator for 2016 [26], and using the cheapest business rate for January 2017 of 10.5 pence per kWh for electricity [27].

It is assumed that broadcast TV will continue up until at least 2025 [28], with the possibility of broadcast TV continuing beyond this. It can therefore be assumed there will be a minimum of 10 years of an adaptive system. If the predicted power savings over 10 years can cover the costs of installation and yearly operating costs, then an adaptive broadcast system will save money in the long run.

D. Estimated Carbon and Electricity Improvements of an Adaptive System

The effects of an adaptive system on the UK DTT network could result in a maximum power savings of 2.1 dB, a 20–35% reduction in ERP while maintaining the same level of coverage as a non-adaptive broadcast system. Table XII shows the potential reductions and savings in power, emissions and running costs of the largest 49 broadcast sites in the UK, assuming a broadcast tower efficiency of 10%. This equates to an electricity reduction of between 33 million and 58 million kWh per year, saving between £3.5 million and £6.1 million and reducing carbon emissions by between 13.7 million and 24 million CO_2e. This means that for an estimated power reduction of 20–35%, an initial installation cost of between £35 million and £61 million ($43.4 million to $75.6 million) for an adaptive system would be fully repaid within 10 years.

VI. SUMMARY AND CONCLUSIONS

In this a paper an adaptive TV broadcast system has been described and evaluated in laboratory conditions using hardware in the loop analysis. Adding adaptive feedback allows the broadcast power to be adapted to better reflect the current propagation effects of the channel. Using a spatially adaptive system could reduce the mean broadcast gain into a channel between 0.8 and 4.6 dB, depending on the range of the fluctuations seen on the channel; when the channel varies over a large range the broadcast powers can be adapted to a greater degree. However, such gain reductions could result in a signal that falls below the threshold value between 40–55% of the time. It is unlikely that such a drop in coverage would be acceptable to a network planning engineer.

To counteract the drop in coverage, a suitable target offset can be used. Matching the offset to the highest observed RoC of the channel can deliver an adaptive system that provides the same level of coverage yet with a reduced mean channel gain. From analysing all possible channel fluctuations described in this paper, the system could deliver a channel mean gain reduction between 0.25 and 2.1 dB while maintaining the same level of coverage as the non-adaptive system. If further losses were acceptable to the network planning engineer, mean gains could be reduced between 0.5 and 3.6 dB. This level of mean gain reduction would result in the signal dropping below the coverage threshold between 2–7.3% of the time.

A spatially adaptive system can be further enhanced by limiting the maximum gain of a channel to the gain that was calculated during the network planning stage. This ensures that broadcast power will never be increased to above the non-adaptive levels, to ensure total broadcast power is reduced and therefore energy is saved. This paper also looked at limiting the minimum gain on the channel to ensure the gain is not set too low. This can limit the total amount of mean gain reduction that can be achieved with an adaptive system. However, simulation work concluded that having a lower gain limit ensured that power was never reduced too far, which could happen when there is a limited amount of feedback available from users or calibration nodes.

This paper has shown that employing a spatially adaptive system can give more options to the network planning engineer; the desired amount of coverage can be traded off against the level of power reduction desired. By employing certain adaptive offsets, channel gain and therefore broadcast powers can be reduced with no to little impact on coverage probability.

Further work would be to expand this research into a field trial, as well as compare energy utilisation with Internet Protocol Television (IPTV) delivery. The utilisation of operational offsets will be included in further simulation work by the author into spatially adaptive broadcast.

The simulation work shown in [1] illustrated a 1 dB reduction in broadcast power based on applying beamforming at broadcast towers, while maintaining the same level of coverage as the omnidirectional broadcast case. This fits with the work shown in this paper with a spatially adaptive system, where further broadcast power reductions have been illustrated. Further simulation work will take into consideration the operational offsets explored in this paper. It is believed that a spatially adaptive broadcast system could provide at least a 1 dB reduction in broadcast powers, with a further 1 dB of power reduction achievable, depending on the propagation conditions and feedback data available.

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John Boyer joined BBC Research in 1985 and early in his career he was involved in the design of antennas for the re-engineering of FM radio from horizontal to mixed polarised transmission and the antenna designs for first phase of the DTT roll-out in the UK. More recently he has worked on full-scale UHF trials of MIMO for television broadcasting, channel sounding for the DVB-NGH group, antenna design and channel sounding for the 'halfRF' HD radiocamera project. His current work mainly comprises investigations into broadcast Wi-Fi.